J. Civil Eng. Mater.App. 2024 (December); 8(4): 245-259

Journal of Civil Engineering and Materials Application
Journal home page: http://jcema.com

Received: 06 October 2024 • Revised: 23 November 2024 • Accepted: 09 December 2024

Review

doi: 10.22034/jcema.2024.218472

Lateral Formwork Pressure in self-compacting Concrete: A Review on Models

Sasan Motaghed [1]*, Fereshteh Ozanzadeh [2], Seyed Amin Asghari Pari [3]

[1] Assistant Prof., Faculty of Engineering, Behbahan Khatam Alanbia University of Technology, Behbahan, Iran.
[2] MSc., Faculty of Engineering, Behbahan Khatam Alanbia University of Technology, Behbahan, Iran.
[3] Associate Prof., Faculty of Engineering, Behbahan Khatam Alanbia University of Technology, Behbahan, Iran.

* Correspondence should be addressed to Sasan Motaghed, Assistant Prof., Faculty of Engineering, Behbahan Khatam Alanbia University of Technology, Behbahan, Iran. Email: motaghed@bkatu.ac.ir

ABSTRACT

Self-compacting concrete (SCC) has revolutionized concrete technology by enhancing construction efficiency and quality through its ability to flow and consolidate without mechanical vibration. This paper reviews various models developed to estimate lateral formwork pressure exerted by SCC during placement, a critical consideration due to the dynamic pressures that exceed those of conventional concrete. The review encompasses foundational theories, including silo theory, and examines models proposed by notable researchers such as Rodin, ACI 622, Adam et al., Gardner, and the hurd Amendment, each contributing unique insights into the factors influencing lateral pressure. Key variables discussed include concrete placement rate, temperature, mix design, and vibration techniques. The findings emphasize the necessity for careful formwork design to mitigate risks associated with excessive lateral pressures while maximizing the benefits of SCC. By integrating recent research and established models, this paper aims to provide engineers and construction professionals with a comprehensive understanding of lateral formwork pressure in SCC applications, ultimately promoting safer and more efficient construction practices.

Keywords: Concrete Placement Techniques, Thixotropic Behavior, Concrete Rheology, Concrete Viscosity

Copyright © 2024, Sasan Motaghed. This is an open access paper distributed under the Creative Commons Attribution License. Journal of Civil Engineering and Materials Application is published by (ISNet); Journal p-ISSN 2676-332X; Journal e-ISSN 2588-2880.

1. INTRODUCTION

Self-compacting concrete (SCC) has emerged as a revolutionary advancement in concrete technology, significantly enhancing the efficiency and quality of construction processes [1-3]. Characterized by its ability to flow and consolidate under its weight without mechanical vibration, SCC is particularly advantageous in complex structural applications where traditional concrete placement methods may prove challenging [4-6]. The unique properties of SCC enable it to fill intricate forms and densely reinforced areas,

resulting in improved structural stability and aesthetic finishes [7,8].

The benefits of using SCC are manifold. SCC's high flowability allows easy placement in complex geometries and congested reinforcement, reducing labor costs and construction time [9,10]. The elimination of vibration minimizes the risk of defects such as honeycombing and cold joints, leading to more durable structures [7,9,11]. SCC typically exhibits lower permeability compared to conventional concrete, improving its resistance to environmental factors [1,3]. The smooth surface finish achieved with SCC is often superior to that of traditional concrete, making it ideal for architectural applications [12,13].Despite these advantages, the use of SCC is not without challenges. The design and production of SCC require diligent attention to mix proportions and material selection, which can lead to increased costs compared to traditional concrete [9,14,15].

Moreover, the complexity of achieving the desired flow characteristics necessitates extensive trial mixes and rigorous quality control measures [16,17]. One significant disadvantage associated with SCC is the lateral formwork pressure it exerts during placement. Due to its high fluidity, SCC can create dynamic pressures that exceed those experienced with conventional concrete. This necessitates careful consideration in formwork design to ensure it can withstand both hydrostatic and dynamic pressures without failure [13,17]. The increased pressure not only compromises formwork stability, but also raises safety concerns on construction sites. Given these factors, engineers and construction professionals must pay close attention to formwork design when utilizing SCC. Properly designed formwork can mitigate risks associated with excessive pressure, ensuring both economic efficiency and safety during construction processes.

The need for robust formwork solutions highlights the importance of understanding the behavior of SCC under various conditions, thus emphasizing the relevance of this review on lateral formwork pressure models. Addressing these challenges through informed design choices is essential for maximizing the benefits of SCC while ensuring safety and cost-effectiveness in construction projects. Thus it is seen that SCC offers significant advantages in construction, including improved flowability and reduced labor needs. However, its high fluidity creates challenges related to lateral pressure on formwork, which must be carefully managed to ensure safety and structural stability. Various models have been developed to predict this pressure, but differences in their assumptions and limitations make it necessary to review them critically. This study aims to compare existing models for lateral formwork pressure in SCC and conventional concrete, highlight their key limitations, and suggest potential improvements for more accurate predictions

2. LATERAL FORMWORK PRESSURE MODELS

Researchers have proposed various criteria and relationships to estimate the maximum lateral formwork pressure and the configuration of the pressure drop diagram. These relationships are derived from laboratory results or theoretical insights. While most regulations and articles focus on conventional concrete, there has been a growing interest in SCC in recent years, leading to the publication of acceptable articles and findings on this topic. Before delving into the models for self-compacting and conventional concrete, it is essential to first discuss silo theory, which underpins some of the models relevant to this discussion.

The silo theory is based on the theory proposed by Janssen, which is primarily concerned with the pressure in silos caused by the storage of granular materials. This theory is the basis of several models for formwork pressure when using SCC. In this model, the horizontal stress is related to the vertical stress using the Janssen parameter (k) [18,19].

$$P_{Horizontal} = K.P_{Vertical} \quad (1)$$

2.1. Rodin 's Model (1952)

In 1952, Rodin investigated published experimental data regarding the lateral pressure exerted by fresh concrete against formwork [20]. He identified several key factors that influence this lateral pressure, including placement rate, vibration, fluidity and mix ratio, concrete temperature, concrete setting time, formwork size, and shape.

Rodin emphasized that formwork design should accommodate two scenarios: for externally vibrated concrete and for non-externally vibrated concrete, which is further categorized into internally vibrated and manually placed concrete. His findings indicated that for externally vibrated concrete, the formwork must be engineered to withstand the full hydrostatic pressure equivalent to a liquid of the same density as the concrete. The results of Rodin's research showed that the fresh concrete behaves like a liquid during vibration, generating lateral pressures similar to those exerted by liquids at corresponding depths. However, various factors can lead to these pressures being lower than those predicted by simple hydrostatic calculations. He showed that a slow vertical placement rate allows the concrete mass below to begin stiffening, which can reduce lateral pressure. Additionally, factors such as internal friction within the concrete, friction between the formwork and concrete, and the migration of pore water also contribute to decreased lateral pressures. Tests have shown that lateral pressure distribution typically starts at liquid-like pressures near the top and reaches a maximum at greater depths. For design purposes, it is common to assume that maximum pressure is uniform at a conservative value. The findings suggest that careful consideration of the aforementioned factors is essential in designing formwork to ensure structural stability during the pouring and setting of concrete.

Rodin's model remains a foundational reference for understanding lateral pressures in concrete formwork design and has influenced subsequent research in this area.

1- Concrete with internal vibration

$P_{Max} = 23.4\ H_{Max}$ (2)

2- Manually-placed concrete

$P_{Max} = 17.2\ H_{Max}$ (3)

H_{Max} is the height at which the maximum pressure occurs (in meters) and is calculated as follows:

$$H_{Max} = 1.63R^{\frac{1}{3}} \quad (4)$$

where R is the Placement rate in meters per hour.

2.2. ACI 622 Trapezoidal Pressure Distribution Model (1958)

In 1958, the American Concrete Institute (ACI 622) recommended that the lateral pressure diagram for concrete formwork be assumed to have a trapezoidal shape [20]. This diagram features a triangular distribution of pressure from the free surface above the concrete pour, extending to a certain depth, beyond which the pressure remains constant until the bottom of the formwork. The ACI guidelines take into account several important variables that influence lateral pressure, including: concrete placement rate and method, concrete flow characteristics, coarse aggregate content, normal size of the aggregate materials, concrete temperature, smoothness and permeability of the formwork material, size and shape of the formwork, method of concrete consolidation, pore water pressure, content and type of cement, depth of concrete placement or concrete head.

These considerations are critical for ensuring that formwork is designed to withstand the pressures exerted by fresh concrete during placement. The trapezoidal pressure distribution model allows engineers to estimate the maximum expected lateral pressures more accurately, thereby enhancing safety and structural stability in concrete construction.

For wall elements :

R<2.14 m/h $P_{Max}=7.19+\frac{785R}{17.78+T} < 95.8\ or\ 23.5\ H$ (5)

2.14<R<3 m/h $P_{Max}=36+\frac{244R}{T+17.78}$ (6)

$P_{Max}=7.19+\frac{1156}{T+17.78}+\frac{244R}{T+17.78} < 95.8\ or\ 23.5\ H$ (7)

R>3 m/h $P_{Max}=23.5H<95.8$ (8)

For column elements

$$P_{Max}=7.19+\frac{785R}{17.78+T} < 143.7 \; or \; 23.5\,H \quad (9)$$

for wall and column elements

$$P_{Max}=\gamma_c H \quad (10)$$

where:

P_{Max}: Maximum lateral pressure in KPa
R: Placement rate in m/h
T: Concrete temperature in °C
H: Concrete head in m

2.3. Adam et al. Model (1963)

In 1963, Adam et al. conducted laboratory studies using large formwork measuring 3 meters in height, 2.5 meters in length, and varying widths. [21] Their experiments aimed to investigate the effects of several factors on formwork pressure, including cement type, admixtures, aggregate size, Placement rate, slump, and vibration**.** From these studies, Adam et al. developed relationships for predicting maximum formwork pressure based on concrete temperature and placement rate. Their findings can be summarized as follows:

The maximum lateral pressure (P_{max}) is influenced by the rate of concrete placement (R) and the temperature (T). The following equations were established:

- For placement rates less than 2 m/h:

$$P_{Max} = 19.6 + 12.3\,R \quad T < 5°C \quad (11)$$

$$P_{Max} = 19.6 + 9.8\,R \quad T = 15°C \quad (12)$$

$$P_{Max} = 19.6 + 8.3\,R \quad T > 25°C \quad (13)$$

The maximum pressure should not exceed 23.54H, where H is the height of the concrete column, which corresponds to the hydrostatic pressure exerted by a liquid with a density of 2400 kg/m³.

The model also considers various factors such as aggregate size, cement type, and slump consistency, which significantly affect lateral pressure.

- For placement rates higher than 2 m/h:

$$P_{Max} = 40.1 + 1.96\,R \quad T < 5°C \quad (14)$$

$$P_{Max} = 35.3 + 1.96\,R \quad T = 15°C \quad (15)$$

$$P_{Max} = 32.4 + 1.96\,R \quad T > 25°C \quad (16)$$

where:

P_{Max}: Maximum lateral pressure in kPa
R: Placement rate in m/h
T: Concrete temperature in °C

2.4. Gardner's Model for Ordinary Concrete (1980)

In 1980, Gardner proposed a model for predicting the maximum lateral pressure (PMax) exerted by ordinary concrete during placement [22]. According to Gardner, this pressure is influenced by several factors, including Depth of vibration, Vibrator power, Placement rate, Concrete temperature, Member dimensions, and Concrete slump.

Gardner assumed that the pressure distribution is hydrostatic up to a certain depth, after which it remains constant until reaching the bottom of the formwork. This assumption allows for a simplified analysis of lateral pressures, which is crucial for effective formwork design.

The equation for predicting the maximum lateral pressure can be expressed as follows:

$$P_{Max}=k\cdot \text{depth} + C \qquad (17)$$

Where k represents a coefficient that accounts for the specific conditions of the concrete placement, and C is a constant that reflects the initial conditions such as concrete temperature and slump.

Gardner's model highlights the importance of various factors in determining lateral pressure, emphasizing that:

Vibration Depth: Deeper vibrations can lead to higher pressures due to increased compaction of the concrete.

Vibrator Power: More powerful vibrators enhance concrete flow and reduce the risk of air entrapment, affecting pressure distribution.

Placement rate: Faster placement rates can increase lateral pressures due to reduced time for consolidation.

Temperature and Slump: Higher temperatures and slumps can alter concrete viscosity, impacting how pressure is distributed against formwork.

Gardner's contributions provide a foundational understanding of lateral pressures in ordinary concrete applications and serve as a reference point for further research and development in concrete formwork design.

$$P_{Max} = 24h_i + \frac{3000HP}{d} + \frac{d}{40} + \frac{400\sqrt{R}}{18+T} + \frac{S-75}{10} < 24H \qquad (18)$$

where:

P_{Max}: Maximum lateral pressure (kPa)
H: Total height of the formwork (m)
h_i: Vibrator immersion depth (m)
d: Minimum dimension of the formwork (mm)
H_P: Vibrator power (horsepower)
R: Placement rate (m/h)
T: Concrete temperature (°C)
S: Slump after using superplasticizer (mm)

2.5. Hurd Amendment to ACI 622 model (2002)

In 2002, Hurd recognized that the equations presented in ACI 622 were too conservative, resulting in a more form-oriented design and increased cost. This was due to the evolution in concrete mix design, mainly with the introduction of chemical admixtures and Portland cement substitutes [23]. Consolidation and placement techniques have also undergone significant changes with the use of highly fluid concrete.

Hurd proposed coefficients in the ACI 622 equations to account for the weight of different units as well as chemical admixtures and cementitious additives.

for walls and columns:

$$P_{Max}=C_w C_c \left(7.19 + \frac{785R}{17.78+T}\right) \qquad 30C_w \text{ (kPa)} \le P_{Max} \le 150\, C_w C_c \text{ (kPa)} \qquad (19)$$

$$P_{Max} \le \gamma_c H$$

where:

ɣc: Unit weight of concrete in kg/m3
H: Head of concrete in meters
P_{Max}: Maximum lateral pressure in kPa
R: Placement rate in m/h
T: Concrete temperature in °C
C_w: Unit weight coefficient, which is calculated as follows:

$$C_w = 0.5 \times (1+\frac{\gamma_c}{23.2}) \geq 0.8 \quad \text{for} \quad \gamma_c < 2240 \text{ kg/m}^3 \tag{20}$$

$$C_w = 1.0 \quad \text{for} \quad 2240 \text{ kg/m}^3 < \gamma_c < 2400 \text{ kg/m}^3 \tag{21}$$

$$C_w = \frac{\gamma_c}{23.2} \quad \text{for} \quad \gamma_c > 2400 \text{ kg/m}^3 \tag{22}$$

Cc in the above equations is the chemical coefficient, which can have one of the values 1, 1.2, or 1.4, depending on the type of cement and additive.

2.6. Vanhove et al. Model (2004)

This model is based on the silo theory and uses the Janssen model [24]. Janssen assumes that at all points, the pressure is on the threshold of slip and has a Coulomb mode[18]. Thus:

$$\tau(h) = \mu P(h) \tag{23}$$

The authors conducted measurements of the friction coefficient between SCC and formwork using a friction meter. They found that, unlike granular materials, fresh concrete exhibits a shear threshold (yield stress), which necessitates adding this yield stress to the friction stress. However, for SCC, they noted that the shear threshold value can be disregarded. The authors pointed out that when applying the Janssen model, it tends to underestimate the lateral pressure exerted by SCC while overestimating both internal friction and friction against the walls. This discrepancy underscores the importance of defining a correction coefficient (α), which reflects the state of contact between grain-to-grain and concrete-to-wall interactions. The value of this coefficient is influenced by various factors, including the placement technique, rheological properties of the concrete, and the released agent. To address these findings, the authors proposed a modified equation for estimating lateral pressure for SCC, which incorporates these considerations to provide a more accurate prediction of formwork pressures during the placement process.

$$P_h(h) = \frac{\rho g A - \alpha \tau_0 (2e+2L)}{\alpha (2e+2L) \mu K} (1 - e^{-\frac{\alpha (2e+2L) \mu K}{A} h}) \tag{24}$$

where:
P_h(h): Lateral pressure at depth h
ρ: Concrete density
g: Gravitational acceleration
e: Form thickness
L: Form width
A: Area (e×L)
α: Correction factor
τ_0: Threshold frictional stress
μ: Friction coefficient
K: Janssen parameter
h: Height

2.7. Khayat and Assaad Model (2005)

In 2005, Khayat and Assaad conducted an extensive study to evaluate the lateral pressure changes of SCC immediately after placement [25]. They utilized a PVC column with a diameter of 0.2 m and a length of 2.8 m for their experiments, alongside a similar column measuring 1.1 m in height to monitor pressure drop until the pressure cancellation, which is associated with the setting process. The SCC was continuously poured from above at a speed of 10 m/h without mechanical compaction. A total of 70 different SCC mixtures were prepared to develop pressure prediction models. The authors determined the breakdown zone from structural breakdown curves to assess thixotropy at various time intervals. They defined the relative lateral stress K as the ratio of lateral stress to the corresponding hydrostatic pressure at that depth. The equations developed to estimate K at different time intervals in relation to thixotropy can be expressed as follows:

1. **Pressure Estimation**: The maximum lateral pressure exerted by fresh SCC was calculated based on hydrostatic principles, considering factors such as:
    - Concrete density (γ_c)
    - Gravitational acceleration (g)
    - Final setting time (t_E)
    - placement rate (v or R)
2. **Pressure Reduction**: The model assumed that the reduction in lateral pressure was primarily due to structural buildup and thixotropic behavior, influenced by hydration processes and pore water content decrease.

The study revealed that the lateral pressure exerted by SCC was consistently lower than hydrostatic pressure. The relationship between maximum lateral pressure (Pmax) and hydrostatic pressure (Phydro) was established using the ratio:

$$K_0=P_{max}/P_{hydro} \quad (25)$$

The model highlighted that factors such as placement rate, temperature, and slump flow significantly affect lateral pressures.

- It primarily focused on placement rate and setting time while neglecting other critical factors influencing formwork pressure.

While Khayat and Assaad's model provided valuable insights into SCC behavior, it had limitations:

- The applicability of the model was limited to specific conditions, including concrete weight assumptions, placement height restrictions, and temperature settings.

Khayat and Assaad's research contributed significantly to understanding lateral pressures in SCC applications. Their findings emphasize the importance of considering various factors affecting formwork pressure, particularly thixotropic properties, which are crucial for effective concrete placement strategies.

$$K_0(\%) = -0.047A_{B1} + 105.8 \quad R^2=0.89 \quad (26)$$

$$K_{100}(\%) = -0.099A_{B2} + 112.2 \quad R^2=0.85 \quad (27)$$

$$K_{200}(\%) = -0.125A_{B3} + 116.8 \quad R^2=0.84 \quad (28)$$

where:

K: Partial pressure equal to Maximum/PHydrostatic (pressure in kPa).

K0, K100, and K200: Specified partial pressure at elapsed times of 0, 100, and 200 minutes after the end of placement , respectively

AB1, AB2 and AB3: Specified structural brakdown zone A_B, at time intervals T1, T2 and T3, respectively

Based on the results, the values of K100 and K200 can be estimated from the AB1 index because the values of AB2 and AB3 have shown a good correlation with the value of AB1.

$A_{B2}=1.14\ A_{B1}$ $R^2=0.96$ (29)

$A_{B3}=1.29\ A_{B1}$ $R^2=0.9$ (30)

By substituting equations (29) and (30) into equations (27) and (28), the values of K100 and K200 can be estimated from the breakdown zone determined in the time interval T1 (0-30 minutes) as follows:

$$K_{100}(\%) = -0.113A_{B1} + 112.2 \quad R^2=0.83 \quad (31)$$

$$K_{200}(\%) = -0.161A_{B1} + 116.8 \quad R^2=0.81 \quad (32)$$

Relationship between apparent viscosity loss and K value: The equations related to K0 values with $\Delta\eta_{app}$ measured via Formula 35, at rotational speeds of 0.3 and 0.9 rps and at 0-30 minutes are as follows:

For N=0.3 rps $K_0(\%)=0.112\Delta\eta_{app}+103.9$ $R^2=0.74$ (33)

For N=0.9 rps $K_0(\%)=-0.168\Delta\eta_{app}+106.7$ $R^2=0.82$ (34)

and

$$\Delta\eta_{app} = (\tau_i - \tau_e)/\dot{\gamma} \quad (35)$$

Where:

τ_i: Initial shear stress

τ_e :Equivalent shear stress

$\dot{\gamma}_e$: Applied shear rate [27]

Effect of concrete head on lateral pressure: In order to evaluate the effect of concrete head on initial pressure, K0 values were determined at different heights along experimental columns filled with concrete to heights of 1, 1.3, 2, 2.4 m. Figure 1 shows the relationships between concrete head and K0 values for SCC with different thixotropy values for mixtures poured at a speed of 10 m/h. As expected, the partial pressure decreases with increasing height due to the longer time taken to fill different parts of the column.

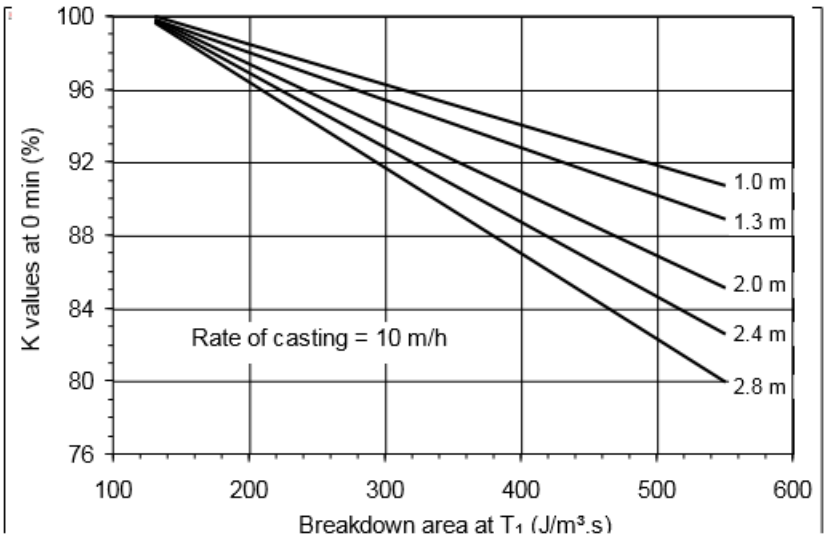

Figure 1. Effect of concrete head on K_0 variations for mixtures with different degrees of brakdown zone [26]

Effect of placement rate on the proposed model:

The placement rate (R) used to obtain the above pressure models is set to 10 m/h. In order to evaluate the effect of R variations on the prediction models, a reference SCC mixture was poured into a 2800 mm high column at R values of 5, 15, 25, and 30 m/h. Based on the results, the following model for variations in placement rate is proposed:

$$K_0(\%)=9.254 \text{ Ln } (R) + 66.5 \qquad R^2=0.95 \qquad (36)$$

The K models previously developed for R=10 m/h can be modified as follows:

K_0 at any given R in terms of (m/h) = ΔK_0 + K_0 measured at 10 m/h (37)

Relationship between dimensions and predicted k values:

Based on the results, a good correlation is established between the relationships between the K values measured directly for SCC, from the 2800 mm test column, and those predicted using Formulas 26 and 28.

2.8. Tejeda-Dominguez Model (2005)

In his research, Tejada-Dominguez developed a model based on the characteristic pressure drop of SCC mixtures, i.e. from the maximum pressure at the end of the pour until the pressure finally reaches zero [28]. This was done using a PVC column of length 920 and diameter 250 mm, with a pressure gauge installed at a height of 152 mm from the floor.

To begin with, Tejeda-Dominguez expressed the horizontal hydrostatic pressure, P = γ"." h, where γ = ρg is the unit weight of concrete, the height of concrete as a function of time (t) and the placement rate (R), i.e. (h) is denoted by Rt, and finally introduced a function that represents the pressure drop, i.e. C(t):

$$P_h = C(t)\gamma Rt \qquad (38)$$

The C(T) function was found to be the best fit for the measured pressure drop characteristic of the tested mixtures with a hyperbolic function:

$$C(t) = \frac{C_o}{(at^2+1)^\alpha} \qquad (39)$$

The expression for lateral pressure in the case of continuous placement is equal to:

$$P_h = \gamma Rt \frac{C_0}{(at^2+1)^\alpha} \qquad (40)$$

where:
γ: unit weight of concrete
R: speed of placement
t: time
C_0: initial pressure
a and α: variables for fitting the function to the pressure drop [28]

The results of using this method have been reported in a large number of annual studies and show that it works satisfactorily. Although this method slightly increases the measured pressure, it does so in a limited way and is also beneficial in terms of safety margin [29].

2.9. Graubner and Proske Model (2005)

This model uses Janssen's theory to predict the relationship between horizontal and vertical pressure exerted by SCC on the formwork [30]. A test column measuring 0.3 × 0.3 × 3.4 m with

measurement points M1, M2, M3 and M4 at heights of 0.3, 1.3, 2.3, and 3.3 m from the floor, respectively, was used to represent the lateral pressure. This column can be seen in Figure 2.

According to the results of this method, the maximum formwork pressure depends significantly on the Placement rate, the setting time of the concrete, and the width of the formwork.

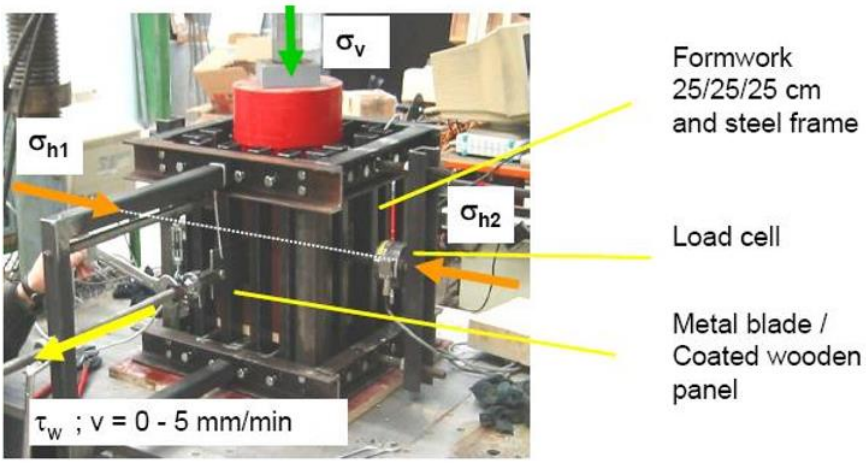

Figure 2. Column used by Graubner and Proske [30]

The equations for predicting lateral pressure are shown below.

$$\sigma_V = e^{-\int \lambda(t)\mu(t)v\frac{U}{A}dt}\left(\int \gamma_c v e^{\int \lambda(t)\mu(t)v\frac{U}{A}dt}dt\right) \quad (41)$$

$$\sigma_h = \sigma_V \lambda(t) \quad (42)$$

where:
σ_V: Vertical pressure
λ: Pressure ratio
μ: Friction coefficient
v: Placement rate
U: Formwork cross-sectional perimeter
A: Formwork cross-sectional area
t: Concrete age
σ_h: Lateral pressure
The parameters λ and μ are obtained according to the diagram or relations contained in the aforementioned article.

2.10. Ovarlez and Roussel Model (2006)

Ovarrles and Russell presented a model to predict the lateral stress exerted by SCC on formwork. The model considers the thixotropic behavior of SCC, where the material initially behaves like a fluid but develops internal structure over time, which leads to reduction in lateral stress. The researchers used the Janssen model and silo theory to measure the maximum SCC concrete formwork stress based on the assumption that this model is valid for a confined elastic material with frictional contact or yield stress in the walls and that according to the Tresca plastic criterion, the maximum stress in the material reaches the yield stress of the material [31].

The elastic theory is used considering small deformations and isotropic material with boundary conditions where: (1) the stress in the walls is equal to τ_0 and (2) the walls are completely rigid. In this method, it is shown that the Janssen parameter or K is related to Poisson's ratio. If the material is incompressible, the Poisson's ratio is equal to 0.5 and therefore the janssen parameter is equal to 1. In this case, the horizontal stress is equal to the

vertical stress. However, concrete is generally compressible because there is always a certain volume of air in the concrete.

The stress at rest in concrete is not constant but increases linearly with time, and since the initial yield stress is small compared to its increase with time, it can be neglected. Ovarles and Russell introduced the time-dependent yield stress parameter as A_{thix} in (Pa/s). Thus, and neglecting the initial yield stress, the evolution of the yield stress at rest (τ_0 (t)) is assumed to be linear in the form of equation 43.

$$\tau_0(t) = A_{thix}t \quad (43)$$

The authors also showed that the lateral stress at a given depth, H(m), is equal to the hydrostatic pressure reduced by the vertical stress in the walls between 0 and the concrete yield stress, τ_0. They also assumed that the vertical deformation due to the concrete's weight (settlement) is sufficient to increase this shear stress to τ_0. Given that the rate of placement (R) is constant, the height of the concrete can be expressed as H = R•t, where t is time (in hours). At the bottom of the already cast concrete, the resting time is equal to (H-e)/R, and at the top, it is equal to zero. By integrating the depth-dependent yield stress, incorporating the janssen parameter, and neglecting the thickness (e for walls or d as the diameter of columns) because they are much smaller than H, the ratio of lateral to hydrostatic stress, or (σ), is calculated using the following expression:

$$\sigma = \frac{\sigma_{Horizontal}}{P\sigma_{hydrostatic}} = K(1 - \frac{HA_{thix}}{\rho geR}) \quad (44)$$

Based on the above assumptions and other observations and calculations, the equations required to predict the maximum lateral stress are presented as follows.

$$\sigma_{Max} = K(\rho gH - \frac{(H-r)^2 A_{thix}}{rR}) \quad (45)$$

where

$\tau_0(t)$: SCC yield stress evolution at rest (Pa)
t: resting time (s)
A_{thix}: Time-dependent yield strength (Pa/s)
σ_{Max}: Maximum lateral stress (kPa)
K: janssen parameter
ρ: Concrete density (kg/m3)
H: Total height of the formwork (m)
r: Radius of a circular formwork or width of a rectangular formwork (m)
R: Concrete placement rate (m/h)

To validate the model, Ovarlez and Roussel compared theoretical predictions of lateral stress with measurements from pressure sensors installed in a formwork with a height of 10 m, a length of 5.44 m, and a width of 0.2 m.

The SCC was pumped from below at a speed of 21.4 m/h. due to the high Placement rate and also the concrete's mobility, led to lateral stress equal to hydrostatic pressure. Pressure sensors were installed at 0.55, 1.95, 3.36 m from the base of the formwork. From the initial lateral stress equal to hydrostatic pressure, the stress drop was monitored.

As the concrete settled in the formwork, the simultaneous formation of the structure was measured using a rheometer. The static yield stress development was then compared with the theoretical shear stress in the formwork walls, which was in perfect agreement.

2.11. Khayat and Omran Model (2011)

From the perspective of this model, the most important parameters affecting the formwork pressure include the height of placement (H), the rate of placement (R), the minimum lateral

dimension of the formwork (D_{Min}), the formation of the internal structure (structural buildup) at rest of the concrete, which is considered as the internal static yield stress after 15 minutes of rest ($PV\tau_{0rest@15min@T_i}$), the maximum aggregate size (MSA) and the waiting period between successive placement (WP) in seconds, which are represented by the parameters f_{MSA} and f_{WP}, respectively [32]. The static yield stress of the structural behavior at rest and ultimately the formation of the internal structure of the concrete can be measured using the experimental method of the portable vane test (PV) or the inclined plate test (IP).

The validity of the prediction model was tested using field measurement results. Based on the author's claim, the results from field measurements are in good agreement with the experimentally predicted values. The lateral pressure prediction equation is shown below.

$$P_{Max}=\frac{\gamma_c H}{100}\left[98-3.82H+0.63R+11D_{Min}-0.021PV\tau_{0rest@15min@T_i}\right].f_{MSA}.f_{WP} \quad (46)$$

where:

P_{Max}: Maximum lateral pressure
γ_c: Unit weight of concrete (kN/m3)
H: placement Depth (m)
R: Placement rate (m/h)
D_{Min}: Minimum lateral dimension of formwork (m)
$PV\tau_{0rest@15min@T_i}$: Static yield stress measured at 15 minutes of settling (Pa)
T_i: Placement temperature (°C)

2.12. Gardner's New Model for SCC - based on field findings (2012)

The new model by Gardner is for predicting the maximum lateral pressure for SCC and is based on the results obtained from field observations [33]. The authors observed that the type and dosage of chemical admixtures used (superplasticizers and retarders in particular) not only affect slump flow, but also significantly affect formwork pressure.

The time required for the slump flow to reach zero (t_0) was chosen as a parameter to describe the hardening/strength behavior of concrete. Since t_0 cannot be measured physically, the parameter is obtained by comparing the slump drop from the time the slump flow reaches 400 mm from the initial value (t_{400}).

$$t_0 = t_{400}\left(\frac{(mm)\ initial\ slump\ flow}{(mm) initial\ slump\ flow-400}\right) \quad (47)$$

$$P = wR\left(t-\frac{t^2}{2t_0}\right)\ for\ t<t_0 \quad (48)$$

$$P_{Max}=\frac{wRt_0}{2}\ \ for\ \ t>t_0 \quad (49)$$

If the formwork filling time or t_h (formwork height/placement rate) is less than t_0, the parameter t_h can be used in equation 48 instead of t.

$$P_h = wR\left(t_h-\frac{t_h^2}{2t_0}\right) \quad (50)$$

where:

h: Placement height (m)
P_h: Limiting lateral pressure (kPa)
R: Placement rate (m/h)
t_{400}: Time for slump to drop to 400 mm
t_h:(h/R) Hours
w: Unit weight of concrete (kg/m3)

3. RESULTS AND DISCUSSION

In this review, several models for predicting lateral formwork pressure in SCC and ordinary concrete were discussed. These models vary in their approaches, based on different theories and parameters. The following key concepts and findings can be summarized:

1. **Rodin's Model (1952)**: This model provides a theoretical framework for predicting lateral pressure in concrete columns, offering insights into the impact of various factors like placement rate and column height.

2. **ACI 622 Trapezoidal Pressure Distribution Model (1958)**: The ACI 622 model explains how pressure spreads in a trapezoidal shape across the formwork. It considers factors such as the height of the concrete, the placement rate, and the concrete temperature, as these influence the pressure on the formwork.

3. **Adam et al. Model (1963):** This model is based on experimental studies using large-scale formwork to establish empirical relationships to predict maximum formwork pressure, emphasizing the influence of concrete temperature and placement rate on lateral pressure distribution.

4. **Gardner's Model for Ordinary Concrete (1980):** This model accounts for factors such as vibration depth, vibrator power, placement rate, and slump consistency. It assumes a hydrostatic pressure distribution up to a certain depth, after which the pressure remains constant. This assumption simplifies lateral pressure analysis and aids in effective formwork design.

5. **Hurd Amendment to ACI 622 model (2002):** This amendment improved the original ACI 622 equations by making them less conservative. As concrete mix designs changed with new chemical additives and cement substitutes, the original equations no longer matched newer concrete mixtures and conditions. Hurd introduced correction factors to adjust for these changes, making formwork design more accurate and efficient.

6. **Vanhove et al. Model (2004):** This model applies silo theory and the Janssen model to SCC, considering friction and yield stress effects. It introduces a correction coefficient to account for the interaction between fresh concrete and formwork and also internal particles, improving the accuracy of pressure predictions.

7. **Khayat and Assaad Model (2005):** This model focuses on SCC pressure reduction over time, attributing it to thixotropy and structural buildup. It emphasizes factors such as placement rate, temperature, and slump flow, demonstrating that SCC typically exerts lower-than-hydrostatic pressure.

8. **Tejeda-Dominguez Model (2005)**: This model introduced the concept of pressure drop over time, emphasizing the maximum pressure at the end of the pour and its gradual reduction. It reflects the behavior of SCC under various placement conditions, providing a more dynamic approach to predicting lateral pressure.

9. **Graubner and Proske Model (2005)**: Using Janssen's theory, this model links vertical and horizontal stresses exerted by SCC on the formwork. It considers key factors like the placement rate and concrete setting time, making it a practical tool for predicting formwork pressure during construction.

10. **Ovarlez and Roussel Model (2006)**: This model predicts the lateral stress exerted by SCC on formwork. It accounts for SCC's thixotropic behavior, showing how yield stress increases over time, reducing lateral pressure. It applies the Janssen model and provides equations to estimate lateral stress based on placement rate, formwork dimensions, and SCC properties.

11. **Khayat and Omran Model (2011)**: This model highlights the importance of factors such as the height of placement, placement

rate, and aggregate size in predicting lateral pressures. It emphasizes the internal static yield stress of concrete as a critical parameter for accurate pressure predictions.

12. **Gardner's New Model for Maximum Lateral Pressure in SCC (2012)**: Gardner's model focuses on the role of chemical admixtures, such as superplasticizers and retarders, in influencing lateral pressure. The model emphasizes the relationship between slump flow and the rate of hardening, offering a more refined approach for predicting pressures in real-world applications.

In summary, while each model provides valuable insights into lateral formwork pressure, they vary in their assumptions, complexity, and applicability to different construction scenarios. The integration of these models into practice requires careful consideration of factors like placement rate, concrete mix design, and environmental conditions.

4. CONCLUSION

Ensuring concrete strength in structures is of paramount importance for structural reliability [34,35]. this review has highlighted the critical aspects of lateral formwork pressure in self-compacting concrete (SCC) and the various models developed to predict these pressures. SCC represents a significant advancement in concrete technology, offering enhanced flowability and consolidation without mechanical vibration. However, its high fluidity poses unique challenges regarding lateral pressure on formwork, necessitating careful design considerations to ensure structural stability and safety during construction. The examination of established models, including those by Rodin, ACI 622, Adam et al., Gardner, and the Hurd Amendment, has provided valuable insights into the factors influencing lateral pressure. Key variables such as concrete placement rate, temperature, mix design, and vibration techniques play essential roles in determining the maximum lateral pressures exerted by SCC. Furthermore, the introduction of correction coefficients and updated methodologies reflects the ongoing evolution in concrete mix design and placement practices. As the construction industry continues to adopt SCC for its numerous advantages, it is imperative for engineers and practitioners to remain informed about the latest research and models. By integrating these findings into formwork design and construction practices, professionals can mitigate risks associated with excessive lateral pressures while maximizing the benefits of self-compacting concrete. Future research should focus on refining existing models and exploring innovative solutions to further enhance the performance and safety of SCC applications in diverse construction scenarios.

UNDING/SUPPORT

Not mentioned any Funding/Support by authors.

.CKNOWLEDGMENT

Not mentioned by authors.

.UTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

'ONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

5. REFERENCES

[1] Khayat KH, De Schutter G. Mechanical properties of self-compacting concrete. Springer; (Vol. 14, p. 161). 2014. [View at Google Scholar]; [View at Publisher].

[2] Motaghed S, Eftekhari N. Multi-Criteria Optimization of Durability Properties of Self-Compacting Concrete Using Artificial Intelligence. Advance Researches in Civil Engineering. 2023 Dec 1;5(4):10-23. [View at Google Scholar]; [View at Publisher].

[3] Motaghed S, Eftekhari N, Kazemifard S, Ozanzadeh F. Prediction of self-compacting concrete plastic cracking using maturity method. In1st International Conference on the Exchange of Scientific

Information in the Fields of Concrete Structures and Materials 2024 May. [View at Google Scholar]; [View at Publisher].

[4] Kazemifard S, Motaghed S, Eftekhari N. NDT prediction of self-compacting concrete strength based on maturity method. Multiscale and Multidisciplinary Modeling, Experiments and Design. 2024 Jun;7(2):1031-43. [View at Google Scholar]; [View at Publisher].

[5] Motaghed S, Ghobadi M, Mirzaie Aliabadi M, Gharayebi Y. Study of the fresh and hardened properties of fiber self-compacting concrete. Journal of Structural and Construction Engineering. 2019 Dec 22;6(Special Issue 4):43-61. [View at Google Scholar]; [View at Publisher].

[6] Khanzadi M, Motaghed S, Asadian Ardakani A. A narrow band method for self consolidation concrete mix ratios determination based on multi-criteria optimization. Concrete Research. 2017 Jan 20;9(2):17-27. [View at Google Scholar]; [View at Publisher].

[7] Motaghed S, Halavat MR, Salehi Vaysi M. Investigation the effect of steel fibers and coarse aggregate ratio on self-compacting concrete properties. Concrete Research. 1970 Jan 1;11(4):95-107. [View at Google Scholar]; [View at Publisher].

[8] Concrete SC. The European guidelines for self-compacting concrete. BIBM, et al. 2005 May;22:563. [View at Google Scholar]; [View at Publisher].

[9] Motaghed S, Ozanzadeh F, Asghari A. Lateral Formwork Pressure in self-compacting Concrete: A Review on Models. Journal of Civil Engineering and Materials Application. 2024 Dec 25(Articles in Press). [View at Google Scholar]; [View at Publisher].

[10] Okamura H, Ouchi M. Applications of self-compacting concrete in Japan. InThe 3rd International RILEM Symposium on Self-Compacting Concrete. Wallevik OH, Nielsson I, editors, RILEM Publications SARL, Bagneux, France 2003 Aug (pp. 3-5). [View at Google Scholar]; [View at Publisher].

[11] Motaghed S, Farhadi Ghafi A, Dadpour A. Investigating the Effect of Iron Ore Powder on Fresh and Hardened Properties of Self-Compacting Concrete. Advance Researches in Civil Engineering. 2022 Dec 1;4(4):16-25. [View at Google Scholar]; [View at Publisher].

[12] Rastegar A, Motaghed S, Dadpour A. Evaluation the Effect of Replacing Cement with Rice Husk Ash on Self-Compacting Concrete Properties. Advance Researches in Civil Engineering. 2023 Jun 1;5(2):22-30. [View at Google Scholar]; [View at Publisher].

[13] Sonebi M, Abdalqader A. Recent development and future trends in self-compacting concrete. InInst. Concr. Technol. Annu. Tech. Symp 2022 Jun (pp. 1-23). [View at Google Scholar]; [View at Publisher].

[14] Motaghed S, Babadi F, Nil Seresht S, Mirzaee Ali Abadi M, Asghari Peri SA, Askari M. Experimental evaluation of the effect of magnetic water on the fresh and hardened pervious concrete properties. Journal of Transportation Infrastructure Engineering. 2020 Oct 22;6(3):89-104. [View at Google Scholar]; [View at Publisher].

[15] Motaghed S, Khooshehcharkh A. Damage–Based Optimal Longitudinal Reinforcement for RC Frames. European Journal of Scientific Research. 2011;50(2):191-201. [View at Google Scholar]; [View at Publisher].

[16] Nielsson I, Wallevik OH. Rheological evaluation of some empirical test methods–preliminary results. InThird International RILEM Symposium, RILEM Pub. PRO 2003 Aug 17 (Vol. 33, pp. 59-68). [View at Google Scholar]; [View at Publisher].

[17] Murtaza M, Zhang J, Yang C, Cui X, Su C, Ramadan AN. Performance analysis of self compacting concrete by incorporating fly ash, coal gangue powder, cement kiln dust and recycled concrete powder by absolute volume method. Construction and Building Materials. 2024 Jun 14;431:136601. [View at Google Scholar]; [View at Publisher].

[18] Janssen HA. Versuche uber getreidedruck in silozellen. Z. ver. deut. Ing.. 1895;39:1045. [View at Google Scholar]; [View at Publisher].

[19] Rodin S. PRESSURE OF CONCRETE ON FORMWORK. Proceedings of the Institution of Civil Engineers. 1952 Nov;1(6):709-46. [View at Google Scholar]; [View at Publisher].

[20] ACI Committee 622. Pressures on Formwork. in ACI Journal Proceedings. 1958. [View at Publisher].

[21] Adam, M., M. Bennasr, and H. Santos Delgado, *Formwork pressure of fresh concrete*. Annales de l'Institut Technique du Bâtiment et des Travaux Publics, Série Béton, 1963(207): p. 403-423. [View at Google Scholar];

[22] Gardner NJ. Pressure of concrete against formwork. InJournal proceedings 1980 Jul 1 (Vol. 77, No. 4, pp. 279-286). [View at Google Scholar]; [View at Publisher].

[23] Hurd MK. Putting the pressure on formwork. Concrete international. 2002 Oct 1;24(10):48-55. [View at Google Scholar]; [View at Publisher].

[24] Vanhove Y, Djelal C, Magnin A. Prediction of the lateral pressure exerted by self-compacting concrete on formwork. Magazine of concrete research. 2004 Feb;56(1):55-62. [View at Google Scholar]; [View at Publisher].

[25] Khayat KH, Assaad J. Use of rheological properties of SCC to predict formwork pressure. InProc., of the 2nd North American Conf. on the Design and Use of Self-Consolidating Concrete (SCC 2005), and the 4th Int. RILEM Symp. on Self-Compacting Concrete 2005 (pp. 671-677). Northwestern Univ., Evanston, IL. [View at Publisher].

[26] Assaad J, Khayat KH, Mesbah H. Assessment of thixotropy of flowable and self-consolidating concrete. Materials Journal. 2003 Mar 1;100(2):99-107. [View at Google Scholar]; [View at Publisher].

[27] Assaad JJ, Khayat KH. Effect of viscosity-enhancing admixtures on formwork pressure and thixotropy of self-consolidating concrete. ACI Materials Journal. 2006 Jul 1;103(4):280. [View at Google Scholar]; [View at Publisher].

[28] Tejeda-Dominguez F. Laboratory and Field Study of Self-Consolidating Concrete (SCC) Formwork Pressure (Doctoral dissertation, University of Illinois at Urbana-Champaign).

[29] Lange DA, Birch B, Henchen J, Liu YS, Tejeda-Dominguez F, Struble L. Modeling formwork pressure of SCC. In3rd North American Conference on the design and use of Self-compacting concrete, Chicago, USA 2008 Nov (pp. 295-300).

[30] Graubner CA, Proske T. Formwork pressure: A new concept for the calculation. InProc. of the 2nd North American Conf. on the Design and Use of Self-Consolidating Concrete (SCC 2005) and the 4th Int. RILEM Symp. on Self-Compacting Concrete 2005 Oct (pp. 605-613). Northwestern Univ., Evanston, IL.

[31] Ovarlez G, Roussel N. A physical model for the prediction of lateral stress exerted by self-compacting concrete on formwork. Materials and Structures. 2006 Mar;39:269-79. [View at Google Scholar]; [View at Publisher].

[32] Khayat KH, Omran AF. Field validation of SCC formwork pressure prediction models. Concrete international. 2011 Jun 1;33(6):33-9. [View at Google Scholar]; [View at Publisher].

[33] Gardner NJ, Keller L, Quattrociocchi R, Charitou G. Field investigation of formwork pressures using self-consolidating concrete. Concrete international. 2012 Jan 1;34(1). [View at Google Scholar]; [View at Publisher].

[34] Motaghed S, Mehrabi Moghaddam A, Moayyeri N. Reliability of Iranian existing residential reinforced concrete structures in seismic events. International Journal of Reliability, Risk and Safety: Theory and Application. 2023 Sep 1;6(2):55-64. [View at Google Scholar]; [View at Publisher].

[35] Motaghed S, Khooshecharkh A. Probabilistic evaluation of the effects of concrete compression strength on the reinforced concrete building damageability. European Journal of Scientific Research. 2011;50(2):202-7.[View at Google Scholar]; [View at Publisher].